1. INTRODUCTION

Background

This Interim Report pertains to the laboratory evaluation of a field-testing apparatus developed by the Centre d'Enseignement et de Recherche pour la Gestion des Ressources Naturelles et de l'Environnement (CERGRENE) of France which uses several small columns to measure particle-settling velocities. This method was adapted for North American application by John Meunier, Inc. The settling-velocity distribution and pollutant content may be used for wet-weather flows (WWF) treatment process selection and design and for evaluation of preliminary or existing process operation.

The U.S. Environmental Protection Agency (EPA) National Risk Management Research Laboratory's Water Supply and Water Resources Division, Urban Watershed Management Branch in Edison (UWMB), New Jersey and John Meunier Inc. in Montreal, Quebec, Canada, established a Cooperative Research and Development Agreement (CRADA) (136-96) to develop settling columns suitable for obtaining particle settling-velocity distribution data for WWF. John Meunier, Inc. and the UWMB are jointly responsible for the prototype apparatus design, construction, testing, and field evaluation as well as procedures to significantly improve selection, design, and operation of full-scale WWF treatment processes that depend on solids-liquid separation through settling and vortex separation. This CRADA will compare the new apparatus with the larger traditional column, the advantages and disadvantages of each method, the projected standard operating procedures, QA procedures, expected results and the limitations for both settling-velocity distribution tests for WWF.

The newer settling testing method is thought to be more amenable to field use because of ease of transport and sampling, and the limited number of samples generated. The comparison attempted to predict whether these tests can capture the solids in WWF, particularly the rapidly settling particles, and whether both systems provide similar design information. Measurements of suspended solids (SS) for several settling times were used to compare the methods. A summary of each column's performance as measured by percent removal for 15 laboratory bench-scale tests is presented and the two methods are compared.

This study is a side-by-side comparison of an existing settling-testing method and a newer settling-testing method. The ongoing study is attempting to determine whether these tests are capable of capturing or representing the rapidly settling particles present in WWF. Two separate column testing methods were fabricated and laboratory tested and preliminary evaluations were made. This interim report reviews the sampling procedures and analytical methods used and presents data and results. Well characterized particles were used in the lab to measure SS concentrations and develop settling-velocity distributions in the columns prior to testing WWF, particularly combined sewer overflow (CSO), which has extremely variable SS concentrations and settling-velocity distributions.

This study was planned in three phases:

- **Phase I:** Preliminary screening - Conducted in a laboratory setting to identify experimental parameters and determine process variables using well characterized particles. Aspects of this phase were performed by both parties (UWMB and John Meunier, Inc.). Procedures were then adjusted to allow for any difficulties encountered during this phase.
- **Phase II:** Laboratory bench-scale testing - The official QA approved experimental test runs of the side-by-side analysis of this phase were conducted in the laboratory of the John Meunier, Inc.
- **Phase III:** Field study - Side-by-side comparative study of the two settling characterization methods (conventional and CERGRENE) will be conducted at an offsite location with actual CSO samples. This side-by-side comparison will determine the limitations and advantages (e.g., cost, setup requirements, correlation to actual settling [in a primary sedimentation tank]) of each approach. Onsite settling column sampling will better represent settling velocities because sample storage and transport may change the naturally occurring settling velocities. Samples will be delivered immediately to the UWMB laboratories and analyzed for SS and other parameters. The Perth Amboy, New Jersey treatment works has been confirmed by both parties for the sampling of CSO.

Objectives

The monitoring and analysis needed for proper selection application, assessment, design, and evaluation of WWF treatment are expensive, time consuming, and complex; however, reliable data collection may save even more costly construction costs by eliminating unnecessary facilities and/or additional controls. The particle-settling-velocity distributions of WWF samples as related to total solids and SS and associated pollutant content are essential for proper assessment of high-rate settling and vortex separation technologies.

The objective of this study is to compare sampling and analytical procedures of two settling column techniques used to characterize the settling velocity of SS in WWF. These results will aid engineers in obtaining pertinent WWF pollution-abatement facility selection and design data by analyzing particle-settling-velocity distribution, and settleable, suspended, floatable fractions and design parameters. These design parameters include facility dimensions, overflow rate, design flowrate, detention time and predicted removal efficiencies.

Low cost, expedient methods to obtain facility-design data or settling-velocity distributions are necessary because WWF characteristics are highly site specific. In order to test the viability of the newly developed CERGRENE columns, a comparison to a settling method with a precedence was needed. Thus a traditional column settling method was used..

Combined Sewer Overflows

The recent EPA National Combined Sewer Overflow Control Policy (59 Federal Register 18688) (CSO Policy) guidance "Combined Sewer Overflow - Guidance for Nine Minimum Controls" (EPA, 1995) requires:

- maximization of flow to the publically owned treatment works (POTW) for treatment
- control of solid and floatable materials in CSOs

and "Combined Sewer Overflow - Guidance for Long-Term Control Plan" (EPA, 1995) further requires:

- characterization, monitoring, and modeling activities as the basis for selection and design of effective CSO controls
- evaluation of alternatives that will enable the permittee, in consultation with the National Pollutant Discharge Elimination System (NPDES) permitting authority, water quality standard (WQS) authority, and the public, to select CSO controls that will meet clean water act (CWA) requirements
- cost/performance considerations to demonstrate the relationships among a comprehensive set of reasonable control alternatives
- maximization of treatment at the existing POTW for wet weather flows

The CSO Policy recommends control/treatment without defining the need for analysis of the flow characteristics and constituents to obtain design information. Determining certain flow characteristics and constituents will optimize the selection and design of unit processes for various degrees of existing physical treatment, e.g., vortex separation, screening, sedimentation, flocculation-clarification, dissolved air flotation, and filtration, and assist in the assessment of newer technologies, e.g., microcarrier coagulation-sedimentation processes. Site specific, storm-event data evaluations are needed for designing CSO treatment facilities, as CSO differs from dry-weather flow (DWF). CSO settleable solids build up and characteristics in the sewer system are a function of the length of the antecedent dry-weather period, sewer slope, drainage area (catchment) size, flowrate, and drainage area soil characteristics, etc., whereas DWF solids characteristics (barring industrial sources) are similar from place to place. Furthermore, suspended and settleable solids concentrations can vary with time during the storm events and from storm to storm.

Past studies have identified urban stormwater runoff as a major contributor to the degradation of many urban lakes, streams, and rivers. Industrial and commercial parking lots, material storage areas, and vehicular service stations are the most significant contributors of a variety of pollutants to WWF. Chebbo et al. (1990) found that the fine particles which make up the majority of SS are also the principal vector of pollution in stormwater during wet weather. Fine particles (< 50 μm) found in stormwater can achieve settling velocities of 2.5 m/h (0.07 cm/s) or more (Chebbo et al., 1990) and 70% to 80 % will deposit within 15 min and more than 97 % after 1 hr.

Settling Columns

The traditional settling method for determining settling-velocity distributions uses side ports to analyze quiescent sampling. Camp (1945) published settling curves using Stoke's Law based on particle settling and Eckenfelder (1966) used it as a design aid for sedimentation processes and for analysis of flocculation. There is substantial variability associated with this method (hereafter Long column).

Currently, only one method for measuring gravity separation is accepted by Standard Methods[1] (SM 2540.F.b; 19th Edition) called "settleable solids". However this method neither determines particle-settling velocity nor enables calculations for settling-velocity-distribution curves. This gravimetric method only measures the initial and final SS concentration after 1 hr. There are no control limits or substantiating data for this method.

This method uses a column of at least 20 cm in depth. A sample is pipetted from the center of the column after 1 hr of quiescent settling to determine the nonsettleable solids. Settleable solids are equal to the initial SS concentration minus the nonsettleable solids concentration.

Traditional Column

The typical Long column is a relatively large apparatus (Camp (1945), Eckenfelder (1966), Dalrymple et al. (1975), in addition to being described elsewhere), standing 1.8 to 2.5 m (6 to 8 ft) high with a diameter of 20 to 30 cm (8 to 12 in.) with side withdrawals evenly spaced along the column depth. The height of the column simulates the effective settling depth which occurs in a sedimentation tank that typically has constructed depths exceeding 2.5 m (8 ft). This column requires an extensive laboratory layout. Various methods have been used to pre-mix the sample before the column test begins, e.g., plunger plates and rotation of the settling column. Depending on specific dimensions between 40 and 80 L (10 and 20 gal) are required to fill the column. The water height in the column is measured. The samples, withdrawn from the side ports sequentially from top to bottom at predetermined time intervals, require further SS analysis. After each set of samples is collected, the depth of the water in the column is measured.

The most notable difficulty with the Long column method is the inability to develop a homogeneous initial SS concentration at the intial samplig time, t_0, due to the heavy particles in WWF. This is partially caused by the length of time required to fill the column and the time required to withdraw samples from all ports sequentially. Pisano et al. (1984) went to the extent of mounting the Long column on a device that allowed axial rotation in an attempt to achieve a better estimate of SS concentration at t_0. It is almost impossible to have a homogeneously mixed sample at t_o using the classical settling column for WWF, which may result in predictions of lower than actual SS fractions.

CERGRENE Columns

CERGRENE (Chadirat et al., 1997) developed a new design that uses a sequence of small columns to analyze the particle settling velocities. Instead of sampling various fractions, with a single sampling device, the CERGRENE protocol uses different settling columns. The

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[1] Standard Methods describes other settling methods which are applicable to the zone settling of sludges. Sludges have significantly higher SS concentrations and different characteristics than CSO.

CERGRENE settling columns, like the long column, are designed to sample for SS concentrations of the WWF in the original sewage matrix.

The new CERGRENE columns have a shorter time to fill (approximately 7 s) and may be more completely mixed at the initial sample time (better representation of t_0). It is thought that the CERGRENE column may account for a wider range of settling solids which may result in establishing better design parameters for WWF. The CERGRENE column was designed for field as well as laboratory use. Settling-velocity-distribution samples taken in the field should give a truer representation of the settling rates of the combined sewage. Settling velocities of samples taken in the field should be faster than samples taken back in the lab or stored in the lab for longer periods of time due to less time allowed for agglomeration.

Other Columns

Other methods developed in Europe are:

Brombach or German (Michelbach and Wöhrle ,1993 and Pisano and Brombach, 1996);
Norwegian Institute for Water Research (NIVA) (Lygren and Damhaug, 1986 and Walker et al., 1993); and
University of Aston U.K. (Tyack et al., 1993)

These methods were specifically designed for the relatively high concentration of heavier particles in storm-generated flows and accordingly, offer several benefits over the Long column. They require less analyses, yielding one sample per time measurement withdrawn from the bottom as opposed to several simultaneous samples from the multiple-side ports. These devices use smaller testing volumes, approximately 4 to 12 L (1 to 4 gal). This is especially true of the German and the NIVA columns (less than 1 m deep and 5 cm wide) which are also more amenable to field use. The Aston column stands at least 2.2 m tall and requires more assembly than the other two as it rotates about the center of the column. These methods provide truer representation of high settling-velocity SS because the concentrated sample is situated above the settling column and dropped into it at t_o.

Unlike the Long and CERGRENE settling column designs which sample the WWF mixture, the Brombach and NIVA methods separate, dry and then reintroduce the SS into clean water. The Aston column was previously tested directly against various forms of the CERGRENE column (Aiguier et al., 1995) which suggested that the derived settling-velocity curves from the various innovative methods tend to give different results. For this reason, only the long and the CERGRENE columns will be analyzed for the purposes of this project.

Theory of Settling Design

Several factors are used in the design of a settling basin including design flow, required detention time and desired percent removal. The first two factors alone could be used to design the physical dimensions of a basin, however, once the third factor is included, the characteristics of the SS in the WWF must be taken into account. For sedimentation tanks Tchobanoglous and

Burton, 1991), the design velocity V_c (m/s) can be related to the liquid depth, D (m) in the tank and the detention time, t_d (s) as follows:

$$V_c = D/t_d \tag{1-1}$$

Given a certain flow through the settling tank, Q (m^3/s), and the plan area of the tank, A (m^2), V_c (m/s) can be related to the overflow rate, q (m^3/m^2/s or m/s), in the following manner:

$$V_c = q = Q/A \tag{1-2}$$

This assumes that all SS with a settling velocity greater than V_c or *q* will be removed with some fraction of all other particles also being removed. For the purposes of this project, the overflow rate will be used in the graphs as a surrogate for a design settling velocity, instead of V_c, which inherently implies a single design settling velocity for a particle instead of a settling-velocity distribution.

Settling can also be broken down into the four types of settling: discrete, flocculant, hindered, and compression (Tchobanoglous and Burton, 1991). The settling velocities of discrete and flocculant particles are of most concern with respect to WWF. The hindered and compression zones of settling are issues of high concentration waste streams, which typically occur at a POTW in secondary-settling tanks and sludge-handling devices or industrial applications.

Various studies used discrete settleable solids and various column devices or settling methods to determine settling velocities. In Stoke's Law (Equation1), the velocity of an ideal sphere is proportional to the square of the particle diameter.

$$v_s = g(\rho_s - \rho)d^2/(18\mu) \tag{1-3}$$

where:
v_s = velocity of sphere, m/s
g = acceleration due to gravity, 981 m/s^2
ρ_s = density of the particle, kg/m^3
ρ = density of the fluid
d = diameter of sphere, m
μ = dynamic viscosity, N·s/m^2

As previously mentioned, settling columns have been used to observe and analyze flocculant settling. WWF is often a combination of discrete and flocculant settling.

While direct measurement of sedimentation efficiency can be made on controls after installation by taking grab samples at the influent and effluent of the controls, the settling column and its predicted removals can assist the engineer or scientist in the selection of design parameters before installation for WWF storage and treatment facilities. Settling columns can help determine the settling velocity distributions for local conditions, e.g., silty WWF may require larger facilities for a desired percent removal, while gritty waste streams could achieve the same percent removals with much smaller facilities. Onsite analysis of this overflow rate derived from the observation of the actual settling velocity distribution is a better design component than the assumption derived from Stoke's Law which only relies on the settling of discrete particles.

In Field Sampling

Sampling devices must be able to capture the heavier SS or settleable solids and not manifest biased results due to stratification. For an automatic sampling device, this means that its intake velocities and ports must be greater than the mainstream velocity and be placed at multiple levels in order to capture the heavier particles near the channel invert, respectively.

The importance of in-field sampling is related to the change in settling properties due to storage and transport. In a comparison of two tests, Dalrymple et al. (1975) showed that two distinct Long column tests had different results on two consecutive days, even though both were run on the same sample. The difference in the test was attributed to the storage of the sample for 24 hr for the second test. This difference in stored samples was also confirmed by CERGRENE (Aiguier et al., 1995), when a fresh sample was compared to the settling rates of three samples stored for 24-hr at different temperatures (room, refrigerated and frozen). Each sample, all collected at the same time, had different settling distributions.

Field Test Site

In identifying field sites for Phase III, the UWMB and John Meunier, Inc., looked for municipalities ready to share technical information regarding location and configuration of combined sewers and overflow sites. The municipalities needed to supply information on drainage area (preferably residential to minimize influences due to industrial sources), the number and volume of overflows per year, SS concentration of overflows and frequency distribution of overflow events. Ideally, candidate sites would not yet have identified or installed treatment options for their CSO's. Additionally, the municipalities would have to be willing to permit the project team access to their facilities during CSO events in the summer of 1999 and to publish results based on data collected.

The City of Perth Amboy, New Jersey operates a combined sewer system and wastewater transfer pumping station that collects combined sanitary sewage, industrial wastewater, and storm runoff from an approximately 7 km^2 drainage area to a regional wastewater treatment plant owned and operated by the Middlesex County Utility Authority. The wastewater transfer pumping facility is located at the junction of Water Street and Sadowski Parkway. A CSO regulator is located about 6 m (20 ft) below the Sadowski Parkway with an overflow weir and 2 m (7 ft) diameter CSO tide-gated outfall to the mouth of the Raritan River.

The pumping station inflow is from the interceptor that discharges into one of two wet-wells each equipped with a mechanical coarse bar screen for removing large debris and protecting the sewage pumps. The screen chamber inflow may be utilized for settling studies, since the inflow is a part of the CSO and will have the same characteristics at the outfall point during storm events. The wet-well is approximately 9 m (30 ft) deep. This is an enclosed facility with 24 hr access and a person on duty. Grit which accumulates in the wet-well is removed from the facility once every three months. A winch and two pumps are also available. This location is approximately five miles away from the UWMB in Edison, NJ.

Field Sampling Review

As background for this project John Meunier Inc. reviewed and wrote an internal report (Champigny et al., 1997) on the state-of-the-art of field-sampling practices. This field of expertise is often overlooked in studies and generally considered as a secondary subject. It was a weak point in many recent characterization studies. The objective of this assessment review was to evaluate the importance of the variability of solids found in sewer systems and to identify the most reliable method to obtain representative samples from a combined sewer. While many of the methods analyzed in the assessment were not developed for the study of WWF, the following general conclusions and recommendations are from the complete internal report were made:

- In dry weather conditions, the vertical concentration gradient of SS can be related to the flow velocity pattern in the pipe or channel.
- A first flush phenomenon has been observed by some researchers.
- Sediments found at the bottom of the channels interact with the SS and have to be included in the sampling.

Two separate sampling systems were recommended:

1. Sampling a complete section of the flow from bottom to top, or
2. Placing sampling port intakes at two points.

This second method would mount one sampling point just above the level of the dry weather flow, near the pipe walls. The second sampling point would be maintained at 60% of the total water level throughout a WWF event.